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ORIGINAL ARTICLE

Avian macro-avoidance of an offshore wind farm in the Taiwan Strait, investigated using surveillance radar

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Abstract The rapid global expansion of wind farms poses potential impacts to bird populations through collision mortality, movement barriers, and habitat displacement. Avoidance, the tendency of birds to maintain distance from wind turbines, plays a critical role in assessing the impacts of wind farms on avian species. In this study, we used marine surveillance radar to monitor avian responses to the Formosa 1 Offshore Wind Farm in the eastern Taiwan Strait. We assessed macro-avoidance by analyzing flight track directions and comparing bird density within and outside the wind farm area. Our findings suggested macro-avoidance rates ranging from 0.33 to 0.69 between March and May, and from 0.83 to 0.89 between July and January. The lower avoidance rates observed in spring could be partially attributed to the high proportion of egrets during this period, as these birds generally exhibited little macro-avoidance behavior in terrestrial observations. Discrepancies between the two methods used to assess avoidance were identified, with radar signal interference from wind turbines likely leading to an overestimation of avoidance rates in the track-density method. Low avoidance between March and May suggested a potentially higher collision risk during spring migration. Further investigation into finer-scale avoidance behaviors and collision rates is essential to understand the ecological impact of wind energy development.

Key words Avoidance, Barrier effect, Collision, Displacement, Offshore wind farm

The demand for wind energy is rapidly growing, driven by its effectiveness in mitigating climate change (Barthelmie & Pryor 2021). In 2023, the global installed capacity of wind energy surpassed the 1 TW milestone, with an annual growth rate projected to be 15% (GWEC 2023). The rapid expansion of wind farms, however, may potentially give rise to significant environmental impacts. The most frequently reported among these impacts, and causing the greatest concern, are adverse effects on birds (Furness et al. 2013; Galparsoro et al. 2022).

Wind farms may affect birds in many ways, most remarkably through collision, barrier effects, and displacement (Drewitt & Langston 2006; Powlesland 2009). Avoidance, the tendency of birds to keep their distance from turbines, links these three risks. On

the one hand, birds with low avoidance of turbines face a higher risk of collisions. On the other hand, birds exhibiting high avoidance may experience the higher cost of barrier effects and displacement due to avoiding wind farms and nearby areas (Humphreys et al. 2015). Avoidance rates are a crucial parameter in avian collision risk modelling (Band 2012; Masden 2015), making them a focal point in wind farm impact studies (Cook et al. 2012; Santos et al. 2022).

Avoidance behavior is typically classified into three scales: macro, meso and micro (Cook et al. 2014; Skov et al. 2018). Macro-avoidance refers to the avian behavior of avoiding wind farms entirely. It is a response taking place outside the wind farm and manifests as displacement and barrier effects. Meso-avoidance is the avian behavior of entering a wind farm while avoiding the very vicinity of turbines. Micro-avoidance refers to the behavioral response

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of birds to a single blade. It is considered as the “last-second” action of a bird in order to avoid collision. The extent of avoidance varies by species, wind farm characteristics, and environmental conditions. For example, swans and geese typically keep their distance from wind farms and exhibit high macro-avoidance (Rees 2012). Gulls, on the other hand, often enter wind farms and avoid collisions through meso-avoidance (Thaxter et al. 2018). Micro-avoidance cases are documented less frequently and may result from adverse conditions, such as poor visibility (Cook et al. 2014).

As birds may alter their flight behavior in response to a wind farm from several kilometers away, radar technology has become essential for studying avian macro-avoidance (Petersen et al. 2006; Krijgsveld 2014; Skov et al. 2018). Radar offers significant advantages over visual observation by covering larger spatial and altitudinal ranges, operating regardless of light and weather conditions, and minimizing observer bias (Hüppop et al. 2019). The primary limitation of radar, however, is its inability to consistently identify bird species. With the exception of avian taxa being linked to radar signals for some high-resolution radars (Zaugg et al. 2008; Bruderer et al. 2010), information about bird species is generally lacking from radar studies. It should also be noticed that a radar echo may represent either an individual bird or a flock, thus radar data requires cautious interpretation. Nevertheless, given its ability to register bird movement continuously and steadily over a large spatial scale, radar is invaluable for wind farm studies. It has been applied in evaluating avoidance rates (Skov et al. 2018; Leemans et al. 2022), quantifying bird flux and flight altitude (Brabant et al. 2021; Largey et al. 2021), estimating collision risks (Welcker & Vilela 2019), and triggering curtailment protocols (Tomé et al. 2017; Salkanović 2023).

The Taiwan Strait, located approximately in the middle of the East Asian-Australasian Flyway, serves as a critical migration corridor for millions of birds, including several endangered species (Yong et al. 2015). However, offshore wind farm development in this region is accelerating due to its high wind-energy potential (Bureau of Energy 2017; People’s Government of Fujian Province 2022). In this study, we employed marine surveillance radar to monitor avian responses to an offshore wind farm in the Taiwan Strait. We analyzed seasonal and diurnal patterns of macro-avoidance, discussed the potential impacts of the wind farm on birds, and proposed

mitigation strategies.

MATERIALS AND METHODS

1) Study area

The Taiwan Strait is a long, shallow channel averaging 60 m in depth connecting the East China Sea and the South China Sea. It extends for about 350 km from southwest to northeast and is up to 180 km wide. The region experiences a subtropical monsoon climate, characterized by predominantly southwest wind in spring and summer, and northeast wind in autumn and winter. Due to its abundant wind resources, the Taiwan Strait is considered one of the world’s premier locations for wind energy development (Fang 2014; Guo et al. 2019).

Our study area, Formosa 1, is the first offshore wind farm in the eastern Taiwan Strait. Located 2–6 km off the northwestern coast of Taiwan (Fig. 1; 24°41’15”–24°43’54” N, 120°47’20”–120°50’06” E), the wind farm covers an area of 10.27 km², with water depths ranging from 15 to 30 m. It comprises 22 turbines with a total installed capacity of 128 MW. The first phase of construction, completed in 2017, involved the installation of two 4 MW turbines. An additional 20 turbines, each with a capacity of 6 MW, were installed in the second phase and commissioned in 2019.

2) Radar survey

To monitor the flight paths of birds, we employed a 12 kW x-band marine surveillance radar (DRS 12A X-class, Furuno Electric Co., Ltd.). The radar was mounted horizontally on the top of a survey vessel, at an elevation of approximately 5 m above sea level. Considering data resolution and coverage, the radius of the radar’s scanning range was set to 6 km.

Ten radar surveys were conducted between March 2021 and January 2022. Surveys were performed on clear days with wave heights below 1 m to minimize interference from wave echoes. When feasible, each survey consisted of continuously scanning for at least 24 hours, capturing data during both day and night. Preliminary observations indicated that birds predominantly flew northward from February to June, southward from July to November, and exhibited random flight direction in December and January. Therefore, the survey vessel was anchored approximately 3 km southwest of the wind farm from March to May and 3 km northwest from July to January, allowing for optimal monitoring of bird tracks as they approached

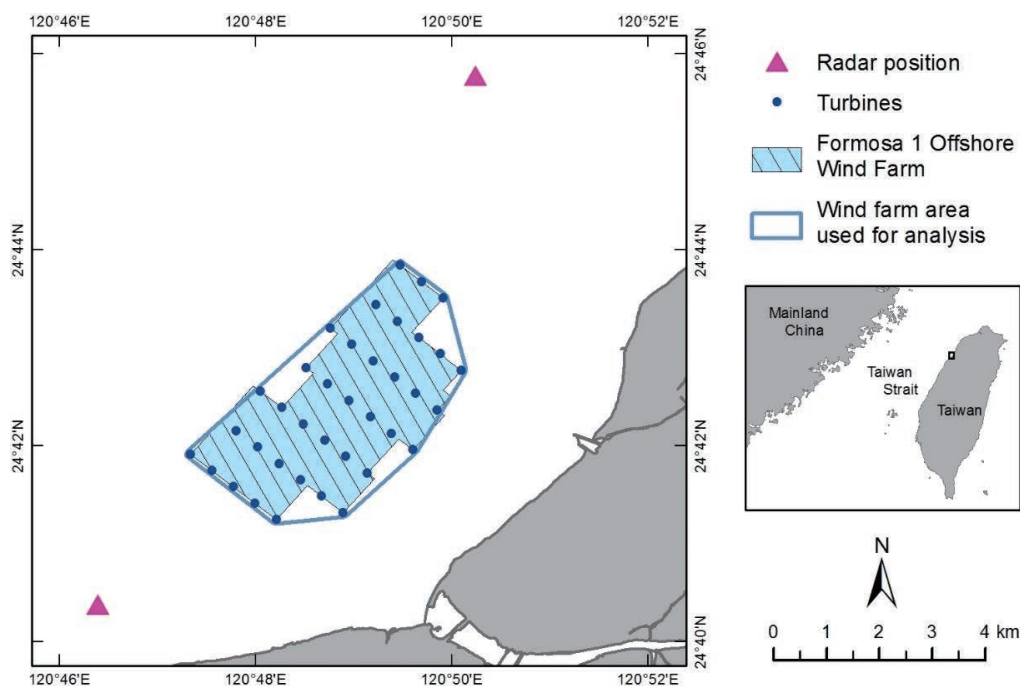


Fig. 1. The study area, Formosa 1 Offshore Wind Farm, and locations of the radar.

the wind farm. Radar images were recorded, and bird tracks were subsequently identified and digitized by trained personnel.

During daylight hours, at least two trained observers were aboard the vessel to record bird species continuously. Birds were searched for in all directions using binoculars (Zeiss Victory Range Finder 10×45 T RF). When birds were detected, they were identified to the lowest possible taxonomic level.

3) Data analysis

We employed two approaches to estimate avian macro-avoidance. The “track-direction method” analyzed the direction of each bird track detected by radar. We constructed a 75 m buffer area (equivalent to the turbine blade length) around each turbine and used the minimum convex polygon of these circles as the wind farm area for analysis (Fig. 1). Each track was viewed as the sequential combination of several component vectors. A track was classified into one of the following categories (Fig. 2):

(a) Unrelated: A track that never headed toward the wind farm, i.e., none of its component vectors pointed toward the wind farm.

(b) Avoidance: A track that initially headed toward the wind farm but later changed direction, no longer heading toward it. In this case, some of the track’s component vectors pointed toward the wind farm, but

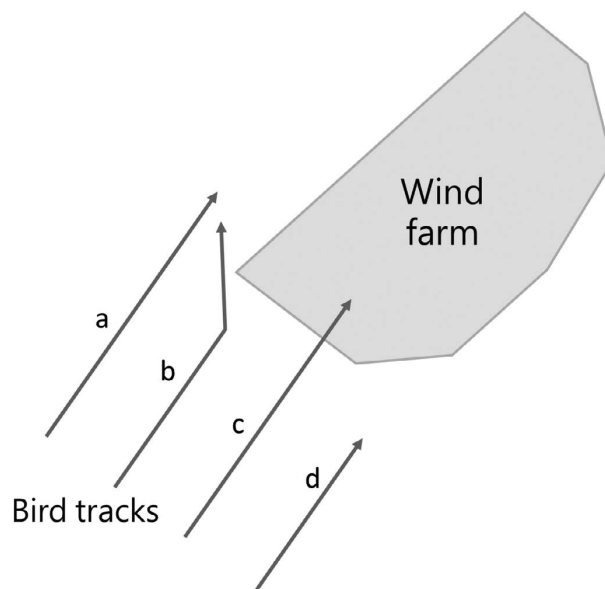


Fig. 2. Illustration of track-direction analysis. (a) a track that never heads toward the wind farm; (b) a track that heads toward the wind farm but later changes direction and heads away from the wind farm; (c) a track that enters the wind farm; (d) a track that heads toward the wind farm but ends too early to determine whether it eventually enters the wind farm.

the final vector did not.

(c) Non-avoidance: A track that entered the wind farm, i.e., it intersected with the wind farm polygon.

(d) Undetermined: A track that was last observed heading toward the wind farm but ended too early to determine whether it eventually entered the wind farm. This situation occurred when the final vector of the track pointed toward the wind farm but was too short to intersect with the wind farm. Such cases could arise when the track entered the blind zone of the radar, or when the signal became too weak to detect while the bird moved further away from the radar.

Tracks in categories (a) and (d) were excluded from the analysis. The macro-avoidance rate based

on the track-direction method (A_{dir}) was then calculated using the following formula:

$$A_{dir} = N_{avoid} / (N_{avoid} + N_{non-avoid})$$

Where N_{avoid} represents the number of tracks in category (b), and $N_{non-avoid}$ represents the number of tracks in category (c). Chi-square tests were applied to compare the avoidance rates between day and night and between seasons.

The second approach, the “track-density method”, assessed macro-avoidance through analyzing the density of bird tracks (Skov et al. 2018). The area

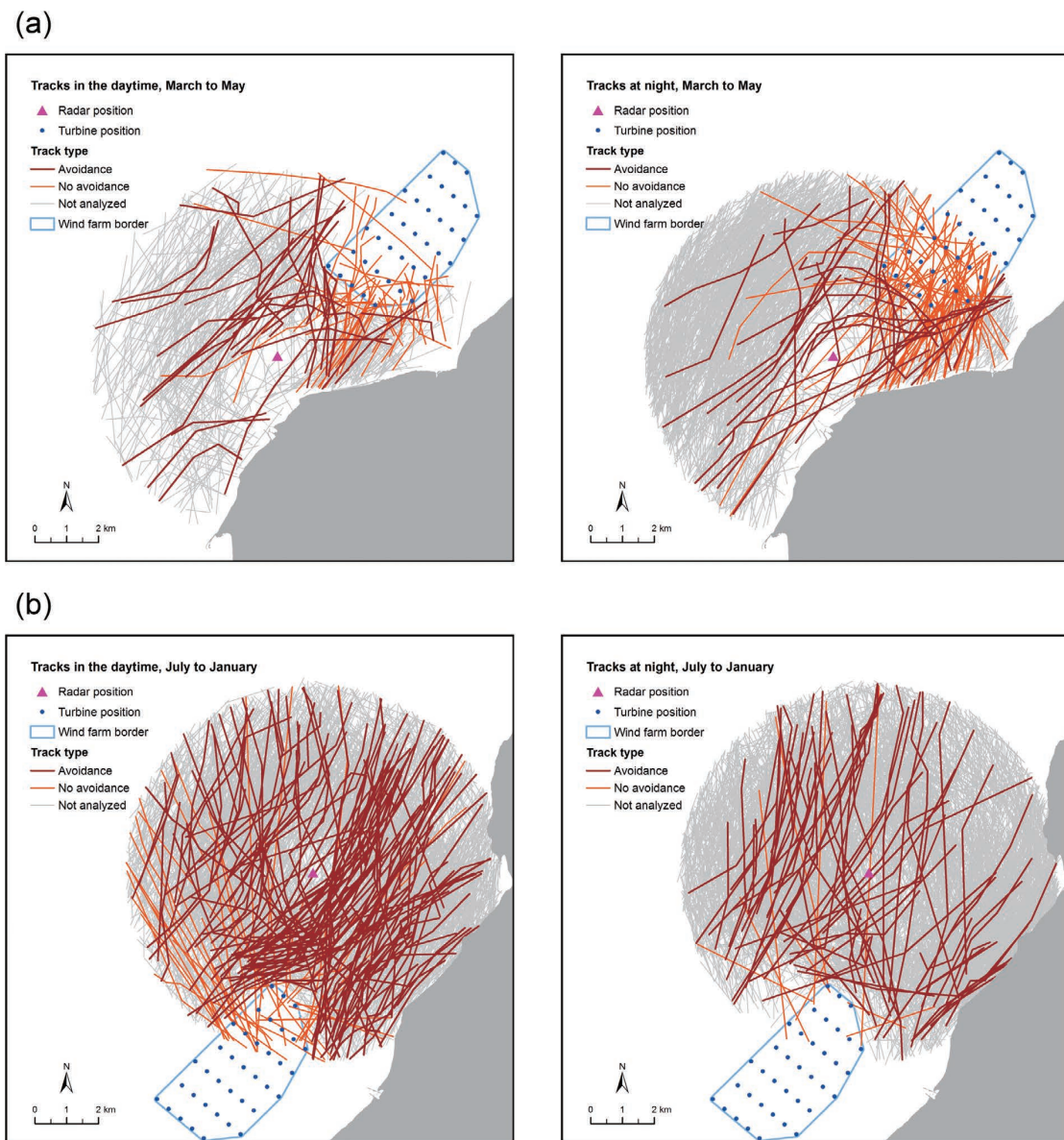


Fig. 3. Bird tracks during the day and at night: (a) from March to May, and (b) from July to January.

scanned by radar was divided using a 100 by 100 m grid. Track density was calculated as the total track length per unit area. Macro-avoidance based on the track-density method (A_{den}) was then estimated using the formula:

$$A_{den} = 1 - N_{in} / N_{ref}$$

Where N_{in} represents the mean track density within the wind farm, and N_{ref} is the estimated mean track density under hypothetical conditions without a wind farm. The reference density N_{ref} can be calculated as the weighted mean of redistributed track densities:

$$N_{ref} = (N_{in} A_{in} + N_{out} A_{out}) / (A_{in} + A_{out})$$

Where N_{out} is the mean track density outside the wind

Table 1. Results of track-direction analysis. N_{avoid} : number of tracks with avoidance; $N_{non-avoid}$: number of tracks without avoidance; A_{dir} : macro-avoidance rate derived based on the track-direction method.

Period	Time	N_{avoid}	$N_{avoid} + N_{non-avoid}$	A_{dir}
March to May	Day	37	84	0.44
	Night	30	121	0.25
	Overall	67	205	0.33
July to January	Day	160	198	0.81
	Night	74	84	0.88
	Overall	234	282	0.83
Year-round	Day	197	282	0.70
	Night	104	205	0.51
	Overall	301	487	0.62

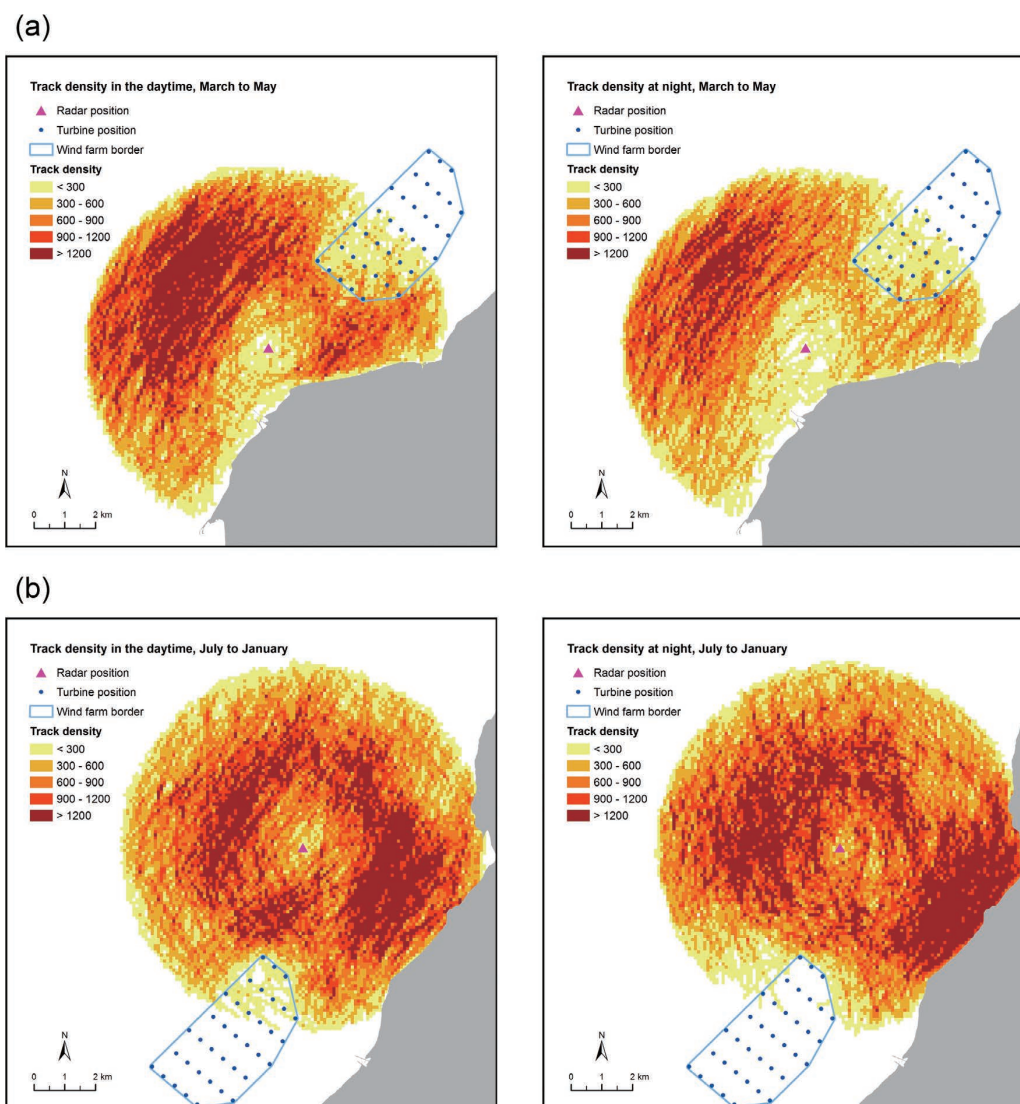


Fig. 4. Bird-track density during the day and at night: (a) from March to May, and (b) from July to January.

farm, A_{in} is the area within the wind farm, and A_{out} is the area outside the wind farm.

The track-density method assumes that any variation in track density is solely caused by the presence of the wind farm. However, the detection performance of a radar decreases with increasing distance (Kamata et al. 2024), leading to a correlation between track density and proximity to the radar. Additionally, because the study area is near the coastline, bird density may also correlate with proximity to the shore. To address these factors, we restricted our analysis to areas where the distances to both the radar and the coastline were similar to those of the wind farm. All analyses were conducted using R (R Core Team 2024).

RESULTS

1) Track-direction analysis

Over the course of 10 surveys, we conducted 190.7 hours of vessel-based radar scans, registering a total of 7,305 bird tracks. Of these, 5,409 tracks never headed toward the wind farm, and 1,409 tracks were directed toward the wind farm but ended too early. Consequently, only 487 tracks were included in the direction analysis. Of these, 301 tracks exhibited avoidance behavior by altering their course to avoid entering the wind farm (Fig. 3), yielding a macro-avoidance rate of 0.62 (Table 1). Daytime avoidance was 0.70, significantly higher than nighttime avoidance at 0.51 (Chi-square test, $\chi^2=17.6$, $df=1$, $P<0.001$).

Seasonally, avoidance between March and May was 0.33, lower than avoidance between July and

January (0.83; Chi-square test, $\chi^2=125.1$, $df=1$, $P<0.001$). During the March to May period, daytime avoidance (0.44) was greater than nighttime avoidance (0.22) (Chi-square test, $\chi^2=7.5$, $df=1$, $P<0.01$). In contrast, during the July to January period, no significant difference in avoidance was detected between day (0.81) and night (0.88) (Chi-square test, $\chi^2=1.7$, $df=1$, $P=0.19$).

2) Track-density analysis

The density of bird tracks within the wind farm was consistently lower than in surrounding areas (Fig. 4). From March to May, mean track density inside the wind farm was 206.4 m/ha, compared to 911.3 m/ha outside (Table 2). This resulted in a derived avoidance rate of 0.69, with little variation between daytime (0.70) and nighttime (0.69). Between July and January, the mean track density within the wind farm

Table 2. Results of track-density analysis. N_{in} : mean track density within the wind farm; N_{out} : mean track density outside the wind farm; N_{ref} : mean track density under the hypothetical situation without a wind farm; A_{den} : macro-avoidance rate derived based on the track-density method.

Period	Time	N_{in} (m/ha)	N_{out} (m/ha)	N_{ref} (m/ha)	A_{den}
March to May	Day	47.0	217.5	157.0	0.70
	Night	157.7	697.1	505.5	0.69
	Overall	206.4	911.3	659.0	0.69
July to January	Day	72.0	526.5	373.5	0.81
	Night	6.3	522.3	348.5	0.98
	Overall	78.4	1,048.8	722.0	0.89

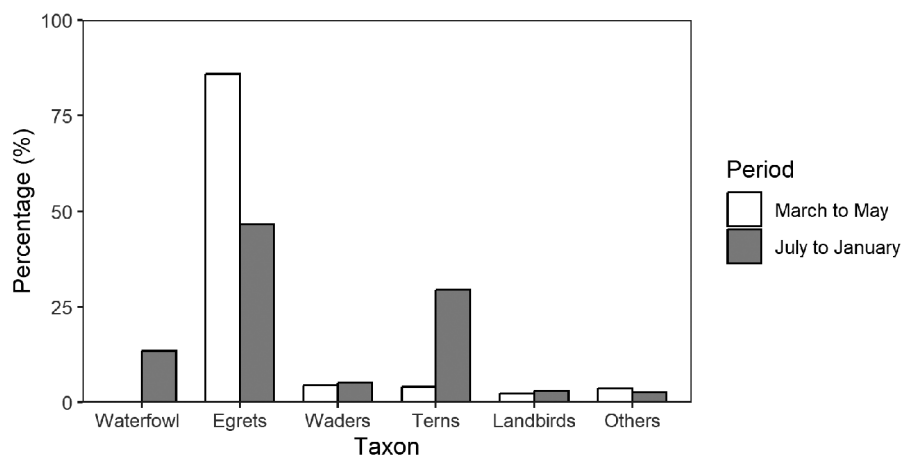


Fig. 5. Bird taxon composition in different periods.

was 78.4 m/ha, whereas it reached 1,048.8 m/ha outside. The derived avoidance rate during this period was 0.89, with a daytime avoidance of 0.81 and a notably higher nighttime avoidance of 0.98.

3) Species composition

From March to May, egrets Ardeidae comprised over 85% of the bird observations (Fig. 5). During the July to January period, egrets remained the most frequently observed taxa (46%), but terns Sterninae (29%) and waterfowl (13%) were also notably prevalent.

DISCUSSION

1) Constraints of the current analyses

In this study, avian macro-avoidance was derived from radar surveys using both track direction and track density. The main limitation of this work is that the analysis was confined to two-dimensional space, as marine surveillance radar registers all detected echoes on a 2D plane. Birds flying at altitudes much higher than the turbines (Hüppop et al. 2006) may not need to alter their flight direction to avoid the structures. Birds flying at risky altitudes may engage in vertical avoidance, adjusting their altitude rather than their horizontal direction (Johnston et al. 2014). The tracks of these birds, however, would be misinterpreted as non-avoidance, as they would appear within the wind farm in 2D radar images. Consequently, the 2D avoidance rates reported here likely underestimate the actual three-dimensional avoidance behavior. The extent of this underestimation may vary by species, as some primarily avoid wind farms by altering horizontal direction (Ueta et al. 2015), while others frequently change their flight altitude (Schwemmer et al. 2023). To capture 3D avoidance, integrated multi-sensor systems (Leemans et al. 2022; Tjørnløv et al. 2023), advanced 3D radars (Everaert et al. 2022), or high-resolution GPS tracking (Schaub et al. 2020; Schwemmer et al. 2023) could be employed.

2) Comparison of two methods of analysis

The track-density method generally yielded higher avoidance values compared with the track-direction method. This discrepancy can partly be attributed to radar-signal interference caused by wind turbines. Wind turbines can generate strong backscatter, which interferes with a radar's ability to detect intended targets (Kong et al. 2013). As a consequence of back-

scatter, bird tracks within the wind farm were relatively difficult to identify. This in turn reduces the sample size available when using the track-direction method, since undetermined tracks were excluded. However, in the track-density method, the interference would lead to an overestimation of avoidance, as the track density within the wind farm was underestimated.

The discrepancy between avoidance values derived by the two methods was more pronounced from March to May than from July to January. In the study area, there appeared to be a flyway with intensive bird traffic parallel to and approximately 3 km from the coast between March and May (Figs. 3(a) and 4(a)). Most of these tracks never headed toward the wind farm (Fig. 3(a)) and therefore did not affect the results of the track-direction analysis. However, in the track-density method, even though the distance to the coast was used as a criterion for selecting the reference site, the influence of the flyway could not be fully eliminated. The wind farm, situated along a section of coastline that curves inward, largely avoided this high-traffic flyway, whereas the reference site did not. This higher track density in the reference site likely contributed to the overestimation of avoidance when using the track-density method.

Based on these findings, we suggest that the track-direction method is better suited for deriving macro-avoidance rates from radar data due to its lower sensitivity to backscatter interference and spatial heterogeneity.

3) Seasonal and diurnal variations

Avian avoidance rates from March to May were generally lower than those from July to January across both methods. One possible explanation for this seasonal difference is the variation in species composition between the two periods. From March to May, egrets were the predominant taxon observed during the daytime. Egrets migrate both during the day and at night (Huang et al. 2021; Lumpkin et al. 2023), with highly variable flight altitudes ranging from less than 100 m to over 1 km (Mateos-Rodríguez & Liechti 2011; Massa et al. 2014). Therefore, it is likely that egrets contributed significantly to the radar echoes at night and at altitudes beyond visual detection. Studies at coastal wind farms generally indicate that egrets exhibit low avoidance behavior. Their abundance is not affected by proximity to wind farms (Xu et al. 2021). Although egrets tend to avoid crossing areas with closely-spaced (200 m)

turbines, they do not perceive widely-spaced turbines (500 m) as barriers (Bai et al. 2021). Therefore, the high proportion of egrets between March and May likely contributed to the observed low avoidance. In contrast, between July and January, terns and waterfowl were also prevalent. Waterfowl are known to exhibit strong macro-avoidance of wind farms (Rees 2012; Krijgsveld 2014). Terns generally avoid wind farms as well, though their level of avoidance may depend on the availability of food within the area of the wind farm (Cook et al. 2012; Krijgsveld 2014).

Nocturnal migrants are often considered more vulnerable to collision due to the challenges of visually detecting turbines at night (Garthe & Hüppop 2004; Furness et al. 2013). However, our results did not support this assumption, as macro-avoidance was highest at night between July and January. Recent studies also suggest that high collision rates at night are not a universal pattern, but tend to occur under adverse weather conditions or at illuminated sites (Marques et al. 2014; Welcker & Vilela 2019). Further research, including information on species composition and flight altitude, is needed to explain the higher nighttime avoidance observed between July and January.

4) Comparison with literature values

Our analysis estimated macro-avoidance values ranging from 0.33 to 0.69 between March and May, and from 0.83 to 0.89 between July and January at the Formosa 1 Offshore Wind Farm. The macro-avoidance so far reported in radar-based studies has varied very widely, from 0.18 to 0.99 (Desholm 2006; Petersen et al. 2006; Krijgsveld et al. 2011; Skov et al. 2018). However, direct comparison of avoidance rates across studies is difficult, as species composition, survey and analysis methods, turbine and wind farm design, as well as spatial-temporal context differ among studies (Cook et al. 2012; Dierschke et al. 2016). Avoidance of wind farms often increases with the density of turbines (Krijgsveld 2014; van Bemmelen et al. 2023). Avian avoidance can also fluctuate based on the wind farm's proximity to nesting or foraging sites, and food availability within the area of the wind farm (Green et al. 2016). Therefore, when evaluating the impacts of wind farms, the use of locally and empirically derived avoidance rates is essential.

CONCLUSIONS

This study represents the first effort to quantify avian avoidance rates at offshore wind farms in East Asia. The bird tracks registered by radar provided clear evidence of avian macro-avoidance responses to the wind farm, which varied with season and time of day. Lower macro-avoidance rates between March and May suggest an increased collision risk during spring migration, highlighting the need for additional mitigation measures during this period. Implementing automated detection systems could help further investigate the meso- and micro-avoidance behaviors of birds and monitor actual collision rates. This information should be integrated into a comprehensive assessment to determine whether a curtailment plan is necessary and how it should be designed. Between July and January, the high macro-avoidance rates indicate that displacement and barrier effects may pose the primary impacts on birds. Given the relatively small size of the Formosa 1 wind farm, the negative effects of habitat loss and increased flight distances are likely minimal. However, with the construction and planning of additional wind farms in nearby areas, cumulative effects must be carefully considered in future environmental impact assessments.

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CONFLICT OF INTEREST

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